NASA Technical Memorandum 79129

EFFECT OF GRAIN ORIENTATION AND COATING ON THERMAL FATIGUE RESISTANCE OF A DIRECTIONALLY SOLIDIFIED SUPERALLOY (MAR-M 247)

P. T. Bizon, R. L. Dreshfield, and
F. D. Calfo
Lewis Research Center
Cleveland, Ohio

April 1979

SUMMARY

Directionally solidified (DS) nickel-base superalloys are being considered for use or are being used for gas turbine airfoils by several aircraft engine manufacturers. Among the properties improved by directional solidification is resistance to thermal fatigue. A primary purpose of this investigation was to determine the effect of off-axis grain growth on the thermal fatigue resistance of uncoated and aluminide coated DS Mar-M 247. DS Mar-M 247 wedge-shaped and round cross-section test bars were grown by the exothermic process such that the growth axis and <100> crystallographic direction were essentially parallel, or at a $7\frac{1}{2}°$, 15°, or 30° angle to the longitudinal axis (leading edge) of the test bar. DS and conventionally cast (random polycrystalline) wedge bars which were both uncoated and coated were cycled in a burner rig between 1070° C and room temperature and periodically examined for initation of cracking. The round cross-section bars were used to perform tensile tests at room temperature and 760° C as well as stress-rupture tests (760° C at 724 MPa and 982° C at 207 MPa) on the same heat of the material.

It was observed that as the angle between the specimen longitudinal axis and growth axis increased, the cycles to initiate cracking decreased for both uncoated and coated bars. For example, the thermal fatigue life for the uncoated material was eight times greater when the specimen longitudinal axis and growth axis coincided as compared to the life when the axes differed by 30°. Coated bars always provided a greater life (about 50 cycles for the DS conditions studied) to initiate cracking than equivalent uncoated bars. It was also noted that the initial cracks were transgranular. This suggests that the increase in elastic modulus, as the misorientation relative to <100> increased, is more important than the intersection of DS grain boundaries with the leading edge of the specimen.

E-9968

INTRODUCTION

Thermal fatigue cracking of a material results from cyclic temperature changes which induce cyclic strains. Thermal fatigue resistance is a major criteria for materials selection for components subjected to fluctuating temperatures. As an example, thermal fatigue cracking is currently a common failure mode of aircraft engine first stage turbine airfoils (ref. 1).

Aircraft gas turbine airfoils fabricated from directionally solidified (DS) nickel-base superalloys are being used or considered for use by several engine manufacturers. The thermal fatigue resistance of nickel-base superalloys can be improved by directional solidification (ref. 2). DS airfoils are normally used with the <100> crystallographic direction essentially parallel to the radial axis of the airfoil. Thus, the angle between the leading and trailing edges of the airfoil and grain boundary is typically limited to a small angle.

The objective of this study was to investigate the effect of off-axis growth and coating on thermal fatigue resistance. A secondary objective was to attempt to correlate short time mechanical properties with measured thermal fatigue resistance.

Wedge specimens (prismatic bars with single-wedge cross section) of Mar-M 247 alloy were cast both conventionally and directionally solidified. The DS wedges were grown by the exothermic process such that the growth axis and <100> crystallographic direction (coincident with the specimen leading edge) were essentially parallel (0°), or at a $7\frac{1}{2}$°, 15°, or 30° angle to the axis of the test bar. Bars were evaluated either uncoated or coated with a chromium enriched pack aluminide. The thermal fatigue tests were conducted at the Lewis Research Center in a Mach 1 burner facility using jet fuel. The bars were cycled so that metal temperatures of 1070° C and room temperature were obtained. Cyclic heating and cooling times were 2 minutes each. In addition, limited room temperature and 760° C tensile as well as stress-rupture (760° C at 724 MPa and 982° C at 207 MPa) tests were performed on uncoated specimens cast by the same procedures from the same heat as the thermal fatigue test bars.

MATERIALS

Alloy

The alloy used in this investigation was the nickel-base superalloy designated Mar-M 247. Table I gives the composition of the master heat of this alloy from which the test specimens were cast. All elements were within the normal specification range for this alloy except chromium. The chromium composition was 7.75% (specification minimum is 8.0%). It was believed that this variation would not affect the results of this program. Tensile and rupture properties of the master heat material are also given in table I. These results exceed the nominal values (as given in ref. 3) for this alloy.

Test Specimens

Both wedge and round cross-section test bars were cast-to-size from the alloy heat by Jetshapes, Inc., Rockleigh, N. J. The geometry of the thermal fatigue wedge specimen (prismatic bar with single-wedge cross-section) is given in figure 1. The round cross-section tensile bars were machined to standard 6.4 mm diameter threaded-end uniaxial specimens conforming with ASTM E8 specification.

The two types of test bars were cast both conventionally and directionally solidified so that random and directional polycrystalline grain structures were obtained. The DS bars were grown by the exothermic process (refs. 4 and 5) such that the growth axis and <100> crystallographic direction were essentially parallel (0°), or at a $7\frac{1}{2}$°, 15°, or 30° angle to the axis of the test bar. Figure 2 shows the wax assemblies for fabricating the two types of DS specimens. Figure 3 shows the typical grain pattern in the off-axis DS thermal fatigue specimens.

Heat Treatment and Coating

All test specimens were heat treated. Only half of the thermal fatigue specimens were coated. The specimen heat treatment and coating is given in table I. This table shows that specimens to be tested uncoated were first given a simulated coating heat treatment of 5 hours at 1024° C before the aging treatment of 20 hours at 871° C which was given to all test specimens. The coating was a chromium enriched pack aluminide designated RT-21 by the vendor. The specified thickness was 0.03-0.08 mm. It was applied by a proprietary process of the Chromalloy American Corporation Research and Technology Division, W. Nyack, N. Y.

TEST FACILITY AND PROCEDURE

Thermal Fatigue

The thermal fatigue test facility is shown in figure 4. Figure 4(a) is a general view with the burner operating while figure 4(b) is a close-up view of the specimens and burner. The facility consisted of an A-1 jet fuel burner operating at Mach 1 velocity mounted between two cooling nozzles. Two thermal fatigue test specimens were mounted in air-cooled holders on a sliding platform. The specimens were moved into and out of the burner and cooling streams by a pneumatic cylinder operated by automatic timers. In this manner one specimen was always in the burner stream except for the transfer time (less than 1 second). The burner and cooling streams impinged perpendicular to the leading edge parallel to the width dimension of the specimens. The specimen temperature was servo-controlled using the output from an infrared pyrometer as the feedback signal to vary the fuel flow to the burner. The infrared pyrometer was focused near the leading edge of the hot zone of the specimen.

The cycling condition for the tests reported here was always burner heating for two minutes to obtain a maximum temperature on the leading edge of 1070° C followed by forced air cooling for an additional two minutes to obtain a minimum temperature of about 25° C. The maximum leading edge temperature was determined by use of an optical pyrometer which was located outside the facility. The indicated reading of the pyrometer was corrected for both the effect of measuring through a glass window and the specimen emissivity being less than unity (ref. 6).

Prior to testing, the leading edge of all specimens was visually inspected by using a microscope with a magnification of 40x so that cracks as small as 0.1 mm could be detected. After 25, 50, 100, 200, 300, and 500 cycles of testing, the specimens were removed from the holders and inspected for cracks. The number of cycles to crack initiation was defined as the average of the number of cycles at the last inspection to show no cracking and the number of cycles at the first inspection to show cracking. Testing was continued beyond observation of initial cracking to a maximum of 500 cycles. Quadruplicate uncoated and coated thermal fatigue wedges were tested at each of the five conditions studied--DS polycrystalline with the growth and test bar axes at a 0°, $7\frac{1}{2}$°, 15°, or 30° angle and conventionally cast random polycrystalline.

Tensile and Stress-Rupture

Using standard 6.4 mm diameter threaded-end round cross-section specimens, both tensile and stress-rupture properties were determined in an air environment. Tests were conducted on uncoated cast-to-size bars at each of the five conditions studied.

For each of the five cast conditions studied, a single tensile test was performed at room temperature while duplicate tensile tests were performed at 760° C. The 0.2%

yield strength, ultimate tensile strength, elongation, and reduction of area were determined. In addition, the modulus of elasticity was determined from the best straight line through the linear portion of the stress-strain curves.

Stress-rupture lives were determined at both 760° C and 982° C. Quadruplicate stress-rupture tests were performed for the five cast conditions studied at 760° C with a stress level of 724 MPa. A single test was performed at 982° C and a stress level of 207 MPa for the conventionally cast and aligned (0°) directionally solidified conditions. Duplicate tests were performed for the nonaligned (growth and specimen axes at a $7\frac{1}{2}$°, 15°, or 30° angle). In addition to life, the elongation and reduction of area are reported for all stress-rupture tests.

RESULTS

Thermal Fatigue

Individual thermal fatigue lives for the uncoated and coated single-edge wedge Mar-M 247 bars are listed in table II with the average of the quadruplicate tests plotted in figure 5. Reproducibility was generally good, with first cracks always being observed at adjacent inspection periods for the quadruplicate tests of any case. Thermal fatigue lives are reported as the average of the number of cycles at the two inspections between which cracking occurred. The lives so measured in this program were all between 12 and 250 cycles. Each cycle consisted of burner heating for two minutes to a maximum leading edge temperature of 1070° C followed by two minutes of forced air cooling to approximately room temperature.

These results show that as the angle between the specimen longitudinal axis and growth axis increased, the thermal fatigue life always decreased, for both the uncoated and coated conditions. As an example, the thermal fatigue life for the uncoated material varied from 200 cycles when the specimen longitudinal axis and growth axis coincided to 25 cycles when the axes differed by a 30° angle. For coated material this variation in thermal fatigue life was between 250 and 75 cycles respectively. The results show that the addition of the coating increased the thermal fatigue life as compared to that for the equivalent uncoated condition. For the data reported herein, a life increase of about 50 cycles for the DS conditions was attributed to the coating.

Another result regarding the thermal fatigue life is the comparison between conventionally cast and directionally solidified material. The thermal fatigue life of conventionally cast specimens was never greater than that for directionally solidified specimens for all the conditions evaluated. However, figure 5 shows that the thermal fatigue life for specimens with the longitudinal axis oriented at an angle of 30° to the growth axis approached the life for conventionally cast specimens. For uncoated Mar-M 247 the thermal fatigue life of specimens with the axes separated by a 30° angle had a life of 25 cycles while that for conventionally cast material was 12 cycles. For coated material the cyclic lives for the same conditions were 75 and 25 cycles, respectively.

Tensile and Stress-Rupture

Individual tensile and stress-rupture results from uncoated 6.4 mm diameter specimens of Mar-M 247 are listed in table III. Average tensile results are plotted in figure 6. The stress-rupture properties are plotted in figure 7.

As shown in figure 6(a) at both test temperatures (room and 760° C) for the DS specimens, the ultimate and 0.2% yield strengths decreased as the angle between the specimen longitudinal axis and growth axis increased. For example, at room temperature the ultimate tensile strength was 1065 MPa when the longitudinal and DS growth axes were aligned compared to 796 MPa when the axes were 30° apart. However, little change was observed in the 0.2% yield strength at angles greater than $7\frac{1}{2}$°. This is similar to the results shown in reference 7 for hafnium modified DS Mar-M 200. The modulus of elasticity, on the other hand, at both test temperatures increased as the angle between the specimen longitudinal axis and growth axis increased. The modulus of elasticity was always less for the DS specimens than for those that were conventionally cast. When the axes differed by 30°, the modulus of elasticity approached that observed for the random polycrystalline condition. As an example, at 760° C the average modulus of elasticity for the random polycrystalline material was 172 GPa, whereas for the case with a 30° angle between specimen longitudinal and growth axes, it was 162 GPa. Similarly for room temperature the results were 241 GPa compared to 222 GPa. Similar behavior is shown in reference 7 for hafnium modified DS Mar-M 200 with the maximum modulus of elasticity occurring when specimen longitudinal and DS growth axes differ by 45°. Reproducibility between the duplicate tests at 760° C was generally good with the greatest variation being observed in the reduction of area results.

The stress-rupture lives shown in figure 7 are presented on the basis of a geometric rather than an arithmetic average. The geometric average is the antilog of the arithmetic average of the log of the rupture lives. The limited stress-rupture results shown in figure 7 show that at 982° C and 207 MPa the life appeared to be independent of the DS growth angle resulting in an geometric average life of about 86 hours. The life of the conventionally cast alloy at these conditions was 71 hours. At the other test condition (760° C and 724 MPa) the data scatter gives results which appear inconclusive except that the geometric average life of the conventionally cast alloy is again less than that for the directionally solidified cases. Both the rupture elongation and reduction of area (DS always greater than conventionally cast) appeared to decrease slightly with an increase in the angle between the specimen longitudinal and growth axes. The DS material always had better rupture ductility than conventionally cast material.

Metallography

Photographs of the leading edge of a typical uncoated specimen at each of the four DS conditions are provided in figure 8. For 0° and 7½° the photographs were taken after 500 test cycles while for the other two angles the photographs were taken after 300 test cycles. This figure shows that the crack growth was transgranular (perpendicular to the leading edge). The cracks did not initiate at the location where the DS grain boundary intersected the specimen leading edge.

Additional photographs of two uncoated wedges after 300 test cycles are given in figure 9. Each wedge specimen is shown as tested and in the etched condition. The etchant used was hydrochloric acid/hydrogen peroxide. Figures 9(a) and 9(b) show a random polycrystalline specimen. Note the intergranular nature of the cracking. Figures 9(c) and 9(d) show the cracks in a specimen where the specimen longitudinal and DS growth axes differ by 7½°. Note how the large crack propagated to the grain boundary and then along the boundary for a short distance before continuing to propagate again parallel to its initial direction. Also, note the considerably less cracking observed in the DS specimen as compared to the random polycrystalline specimen after an identical number of cycles (300).

Examination of failed tensile and 760° C stress-rupture specimens was also performed. The fractures appeared to be transgranular and could not be related to intersections of DS grain boundaries with the specimen surface.

DISCUSSION

Previous research (ref. 2) for other nickel-base alloys indicated that directionally solidified polycrystalline materials had superior thermal fatigue resistance compared to the random polycrystalline form of the same alloy. This was attributed to the lower modulus of elasticity and absence of transverse grain boundaries in the DS alloy as compared to the conventionally cast alloy. This interpretation is consistent with the fact that the thermal strain is equal to the product of the coefficient of thermal expansion and the temperature difference. It is generally accepted that the coefficient of thermal expansion for cubic metals is independent of grain structure, being dependent only on composition. The thermal fatigue tests reported herein were designed so that all specimens experienced identical thermal excursions. Therefore, in these tests using specimens of the same geometry and composition, as well as an identical test condition, the total leading edge strainrange for all cases was constant. Comparing specimens with different moduli of elasticity, the lower the modulus of elasticity, the greater the elastic and the smaller the plastic strain components, which results in greater thermal fatigue life.

The results of the present research verify this observation for the comparison between conventionally cast and aligned DS material, as well as for the nonaligned DS material. For example, the thermal fatigue life of uncoated aligned directionally solidified Mar-M 247 alloy was about 16 times (200 cycles compared to 12 cycles) that of the uncoated random polycrystalline form while the 760° C modulus of elasticity of the aligned DS alloy was 60% (103 GPa compared to 172 GPa) of that of the random polycrystalline form. In addition, as the angle between the longitudinal and DS growth axes increased for the DS material, it was again observed that the thermal fatigue life decreased while the modulus of elasticity increased. For axes separated by 30°, the thermal fatigue life had decreased almost to that observed for conventionally cast material while the modulus of elasticity had increased almost to that of the conventionally cast material. For the conventionally and DS cast material, no single mechanical property other than modulus of elasticity showed a clear correlation with thermal fatigue resistance.

Another point to note is the effect on thermal fatigue life of the intersection of DS grain boundaries with the leading edge for the nonaligned specimens. The photographs of the uncoated material showed the cracking in the DS specimens to be transgranular. For the nonaligned DS material, the cracks were not observed to initiate at the surface grain boundary and propagate for any great length along the grain boundary. Rather they initiated at the leading edge and propagated almost perpendicular to the leading edge into the wedge across the grain boundaries.

This can be further emphasized by noting the effect of coating on thermal fatigue life. For the nonaligned DS specimens, if cracking initiated at the intersection of a DS grain boundary with the leading edge, it would be expected that coating would have improved the thermal fatigue life so that all coated nonaligned specimens would have about the same life as the coated DS aligned specimens (250 cycles). This, of course, was not observed. The average thermal fatigue life of the nonaligned coated DS specimens varied from 175 to 75 cycles.

CONCLUDING REMARKS

The combination of test data and metallurgical observations indicate that nonalignment of the airfoil longitudinal axis and DS growth axis has a more significant effect on thermal fatigue life than does the intersection of a DS grain boundary with the airfoil leading edge. This is believed to be due mainly to the effect of the modulus of elasticity of the material. Thus, it was noted that as the angle between the specimen longitudinal axis and growth axis increased, the modulus of elasticity increased and the thermal fatigue life decreased. When the angle reached 30° both the modulus of elasticity and thermal fatigue life approached that of conventionally cast (random polycrystalline) material. This is similar to the results shown for thermomechanical fatigue crack growth rates in reference 7. The crack growth rate for pre-cracked material in that investigation was shown to be equal for conventionally cast and 45° off-axis DS material. Furthermore, none of the other mechanical properties measured showed a correlation with thermal fatigue life. This investigation suggests that the rejection criteria applicable to DS casting of gas turbine airfoils which concerns the intersection of DS grain boundaries with the leading and trailing edge of the airfoil should be reexamined. If the majority of the DS grains are aligned in the low modulus of elasticity direction, intersection of a DS grain boundary with the leading or trailing edge of an airfoil would probably not be detrimental to performance. It should be emphasized, however, that the results of the present investigation, when considered in conjunction with the results of reference 7, clearly show that to obtain maximum thermal fatigue and low cycle fatigue resistance, the low modulus direction (<100>) must coincide with the airfoil longitudinal axis.

SUMMARY OF RESULTS

The effect of off-axis grain growth on thermal fatigue resistance was determined for uncoated and pack aluminide coated directionally solidified (DS) Mar-M 247 alloy. DS Mar-M 247 single-wedge shaped bars were grown by the exothermic process such that the growth axis (and <100>) was essentially parallel, or at a $7\frac{1}{2}°$, 15°, or 30° angle to the longitudinal axis of the test bar. DS and conventionally cast bars which were both uncoated and coated were cycled in a high velocity (Mach 1) burner rig resulting in metal temperatures of 1070° C and room temperature. Periodic inspections for onset of cracking were made. Limited tensile and stress-rupture tests of uncoated DS and conventionally cast-to-size specimens were also performed. Major results are as follows:

1. As the angle between the specimen longitudinal axis and growth axis increased from 0° to 30°, the thermal fatigue life always decreased for both the uncoated and coated conditions. For example, the thermal fatigue life for the uncoated material was eight times greater when the specimen longitudinal axis and growth axis coincided as compared to the life when the axes differed by 30°.

2. Presence of the aluminide coating always increased thermal fatigue life as compared to that for the equivalent uncoated condition. Life increases of about 50 cycles for the DS conditions were attributed to coating.

3. The thermal fatigue life of directionally solidified specimens was never less than that for conventionally cast specimens for all conditions evaluated. However, the thermal fatigue life for specimens with the growth axis oriented 30° to the longitudinal axis approached the life for conventionally cast specimens.

4. Metallurgical examination revealed that the initial thermal fatigue cracking in all of the DS Mar-M 247 specimens was transgranular and did not originate at the intersection of DS grain boundaries with the leading edge of the specimen. This is in contrast to the thermal fatigue cracking in the conventionally cast specimens which was intergranular. Room temperature tensile as well as 760° C tensile and stress-rupture DS specimens all fractured in a transgranular mode.

5. For the DS Mar-M 247 specimens, the ultimate tensile

strength decreased as the angle between the specimen longitudinal axis and growth axis increased. The 0.2% yield strength decreased from 0° to 7½° and then remained essentially constant through 30°. The modulus of elasticity increased as this angle increased. For an angle of 30° the modulus was only slightly lower than that observed in the conventionally cast condition.

REFERENCES

1. Simmons, W. F.: Current and Future Materials Usage in Aircraft Gas Turbine Engines. MCIC-73-14, Battelle Columbus Labs., (AD-766334), 1973.

2. Bizon, P. T.; and Spera, D. A.: Comparative Thermal Fatigue Resistances of Twenty-Six Nickel- and Cobalt-Base Alloys. NASA TN D-8071, 1975.

3. High Temperature High Strength Nickel Base Alloys. The International Nickel Company, Inc. Third ed., 1977.

4. Kanaby, R. R.; et. al.: Directional Solidification of Superalloys. DDAD-EDR-9193, General Motors Corp., 1977. (AFML-TR-77-126, AD-B025972L.)

5. Sink, L. W.; Hoppin, G. S. III.; and Fujii, M.: Low-Cost Directionally-Solidified Turbine Blades, Vol. 1. (AiResearch 21-2953-1, AiResearch Manufacturing Company of Arizona; NASA Contract NAS3-20073.) NASA CR 159464, 1979.

6. Bizon, P. T.; and Calfo, F. D.: Effect of Heating Method on Stress-Rupture Life. NASA TM-73738, 1977.

7. Gemma, A. E.; Langer, B. S.; and Leverant, G. R.: Thermomechanical Fatigue Crack Propagation in an Anisotropic (Directionally Solidified) Nickel-Base Superalloy. Thermal Fatigue of Materials and Components, Am. Soc. Test. Mater. Spec. Tech. Publ. 612, 1976, pp. 199-213.

TABLE I. - MATERIALS AND SPECIMEN CHARACTERIZATION

Mar-M 247 master heat composition

Heat number	Weight percent																ppm				
	C	Cr	Ni	Al	Ti	Co	W	Mo	Ta	Hf	Zr	B	Mn	S	Si	Cu	Fe	Pb	Bi	Se	Te	Tl
7-10187	0.14	7.9	Bal.	5.6	1.0	10.6	9.8	0.6	3.2	1.4	0.035	0.019	0.03	0.006	0.115	0.050	0.115	<1.0	<0.3	<0.5	<0.5	<0.5

Mar-M 247 master heat mechanical tests

Test temperature, °C	Ultimate tensile strength, MPa	0.2% yield strength, MPa	Rupture stress, MPa	Rupture life, hr	Elongation, %	Reduction of area, %	Plastic elongation, %
25	1125	950	---	---	7	10.8	-
760	----	---	724	112	--	----	4
982	----	---	220	67	15	11.8	-

Specimen heat treatment

Uncoated	Simulated coating treatment of 5 hr at 1024° C Aged for 20 hr at 871° C
Coated	Aged for 20 hr at 871° C

Specimen coating

Chromium enriched pack aluminide RT-21 (Chromalloy American Corporation Research and Technology Division proprietary process).

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE II. - THERMAL FATIGUE CYCLES TO CRACK INITIATION

[Cyclic conditions: 1070° C (2 min) ⇄ 25° C (2 min).]

Surface condition	Angle between specimen longitudinal and DS growth axes, deg	Specimen number	Cycles to initial crack	Average cycles to initial crack
Uncoated	0	U01	150	200
		U02	150	
		U03	250	
		U04	250	
	7½	U71	75	94
		U72	75	
		U73	150	
		U74	75	
	15	U151	75	66
		U152	38	
		U153	75	
		U154	75	
	30	U301	12	25
		U302	38	
		U303	38	
		U304	12	
	Equiaxed	UE1	12	12
		UE2	12	
		UE3	12	
		UE4	12	
Coated	0	C01	250	250
		C02	250	
		C03	250	
		C04	250	
	7½	C72	150	175
		C73	150	
		C74	250	
		C75	150	
	15	C151	75	131
		C152	150	
		C153	150	
		C154	150	
	30	C301	75	75
		C302	75	
		C303	75	
		C304	75	
	Equiaxed	CE1	12	25
		CE2	38	
		CE3	38	
		CE4	12	

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE III. - TENSILE AND STRESS-RUPTURE PROPERTIES

Tensile properties

Temperature, °C	Angle between specimen longitudinal and DS growth axes, deg	Specimen number	0.2% yield strength, MPa	Ultimate tensile strength, MPa	Modulus of elasticity, GPa	Elongation, %	Reduction of area, %
25	0	0-1	863.2	1065.2	131	10.7	10.8
↓	7½	7-1	614.3	972.9	152	12.9	16.0
↓	15	15-1	76[illegible].4	894.9	152	11.8	14.9
↓	30	30-1	792.9	795.7	222	4.3	18.3
↓	Equiaxed	E-1	883.2	972.2	241	3.8	7.7
760	0	0-2	950.1	1112.6	103	3.3	6.0[a]
↓	0	0-3	896.3	1127.3	103	9.6	14.5
↓	7½	7-2	803.9	900.4	117	11.5	23.1
↓	7½	7-3	801.[illegible]	1032.8	124	10.8	12.4
↓	15	15-2	752.9	869.4	131	6.4	13.3[a]
↓	15	15-3	832.[illegible]	1018.4	110	10.0	23.2
↓	30	30-2	759.8	878.4	152	7.5	17.0
↓	30	30-3	763.3	826.7	172	9.2	17.6
↓	Equiaxed	E-2	862.5	1073.5	172	6.1	5.9
↓	Equiaxed	E-3	842.5	1082.5	172	8.1	9.[illegible]

Stress-rupture properties

Temperature, °C	Stress, MPa	Angle between specimen longitudinal and DS growth axes, deg	Specimen number	Life, hr	Elongation, %	Reduction of area, %
760	724	0	0-4	214.0	14.5	19.4
↓	↓	↓	0-7	185.4	----[b]	19.6
↓	↓	↓	0-8	211.9	15.5	24.9
↓	↓	↓	0-9	240.5	11.5	17.5
↓	↓	7½	7-4	16.2	10.9	19.5
↓	↓	↓	7-6	186.6	15.3	21.7
↓	↓	↓	7-7	118.2	13.4	19.5
↓	↓	↓	7-8	25.5	18.1	20.6
↓	↓	15	15-4	198.6	15.0	22.5
↓	↓	↓	15-6	276.7	9.5	16.5
↓	↓	↓	15-7	226.6	14.5	18.9
↓	↓	↓	15-8	224.7	15.3	22.8
↓	↓	30	30-4	5.7	4.8	12.9
↓	↓	↓	30-6	196.0	16.9	24.0
↓	↓	↓	30-7	149.4	16.3	22.3
↓	↓	↓	30-8	50.9	7.9	23.1
↓	↓	Equiaxed	E-6	17.3	1.6	4.9
↓	↓	↓	E-7	135.7	4.3	6.7
↓	↓	↓	E-8	102.3	3.6	5.7
↓	↓	↓	E-9	10.5	1.3	1.9
982	207	0	0-5	94.4	36.6	61.4
↓	↓	7½	7-5	96.4	35.8	58.0
↓	↓	7½	7-9	70.1	36.2	60.7
↓	↓	15	15-5	104.4	30.4	59.3
↓	↓	15	15-9	73.2	34.0	50.7
↓	↓	30	30-5	105.0	27.6	59.0
↓	↓	30	30-9	65.9	27.6	41.1
↓	↓	Equiaxed	E-5	70.5	7.7	14.2

[a]Specimen failed near radius.
[b]Not determined.

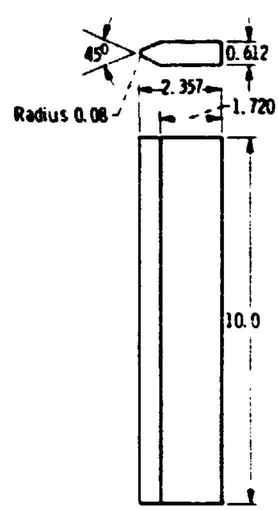
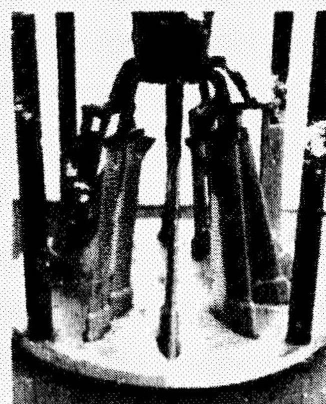
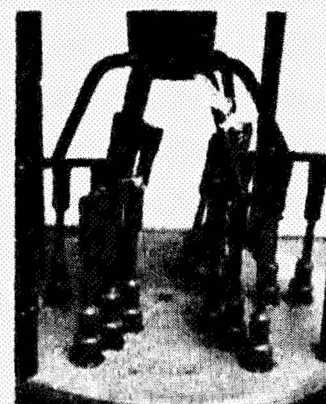


Figure 1. - Geometry of thermal fatigue wedge specimen. (All dimensions in cm unless indicated otherwise.)



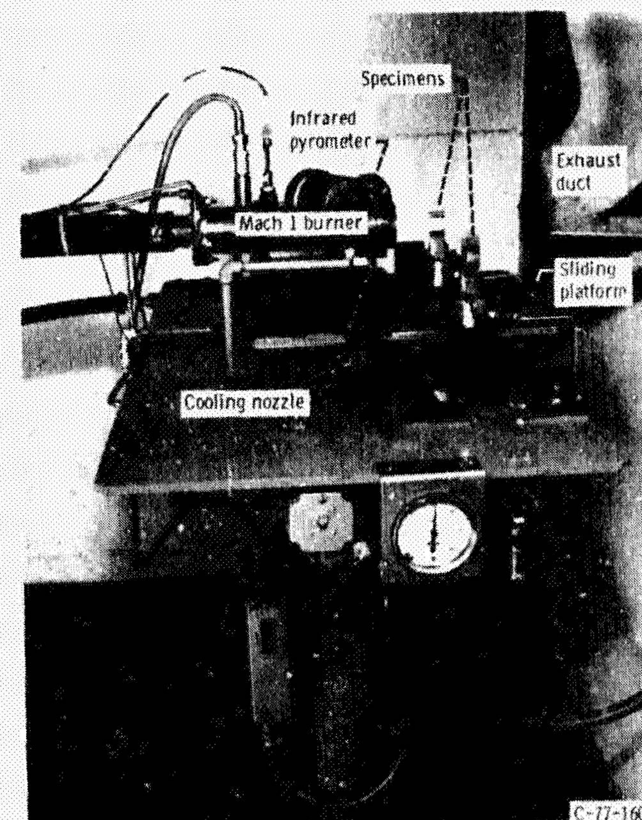
(a) Thermal fatigue.



(b) Tensile and stress rupture.

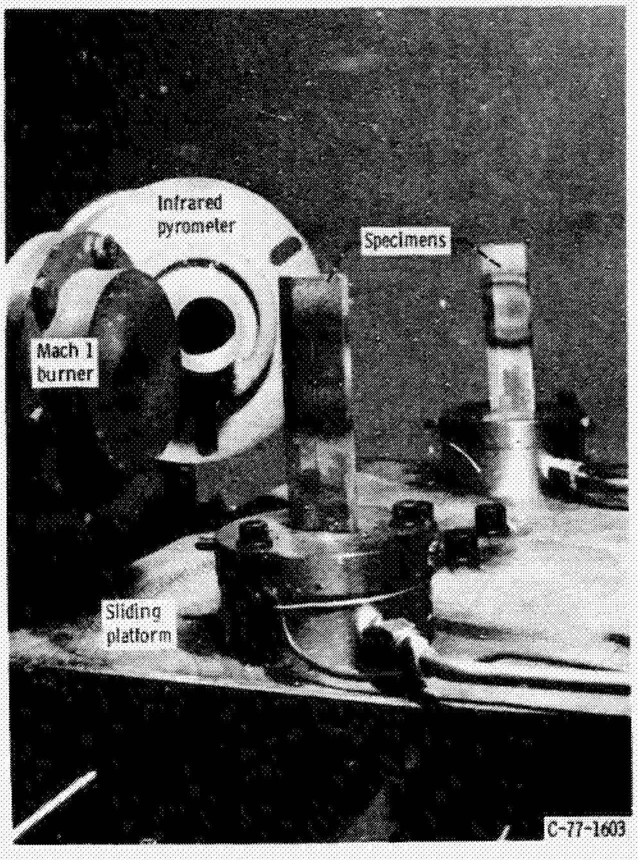
Figure 2. - Wax assemblies for fabricating off-axis directionally solidified specimens.

Figure 3. - Typical grain pattern in off-axis directionally solidified (DS) thermal fatigue specimens. The specimen longitudinal and DS growth axes are shown at a 30°, 15°, and 7-1/2° angle respectively. (Photographs courtesy of Jetshapes, Inc.)



(a) General view.

Figure 4. - Thermal fatigue test facility.



(b) Close-up view.

Figure 4. - Concluded.

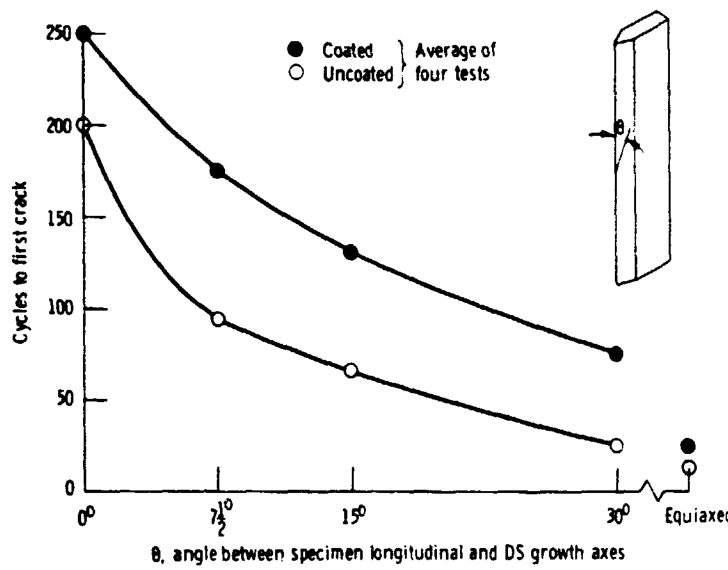


Figure 5. - Effect of grain orientation on thermal fatigue life of Mar-M 247 alloy. [Burner heating 1070° C (2 min) ⇄ 25° C (2 min)].

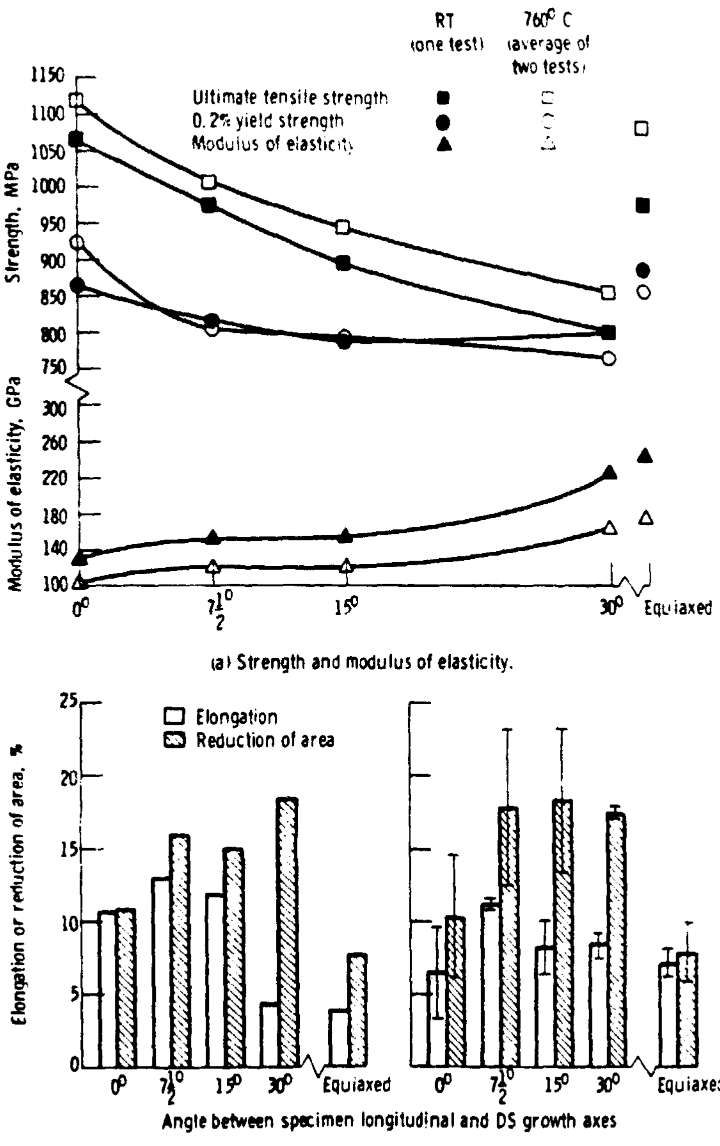


Figure 6. - Variation of tensile properties for directionally solidified (DS) and conventionally cast Mar-M 247 alloy as a function of DS grain orientation angle.

ORIGINAL PAGE IS
OF POOR QUALITY

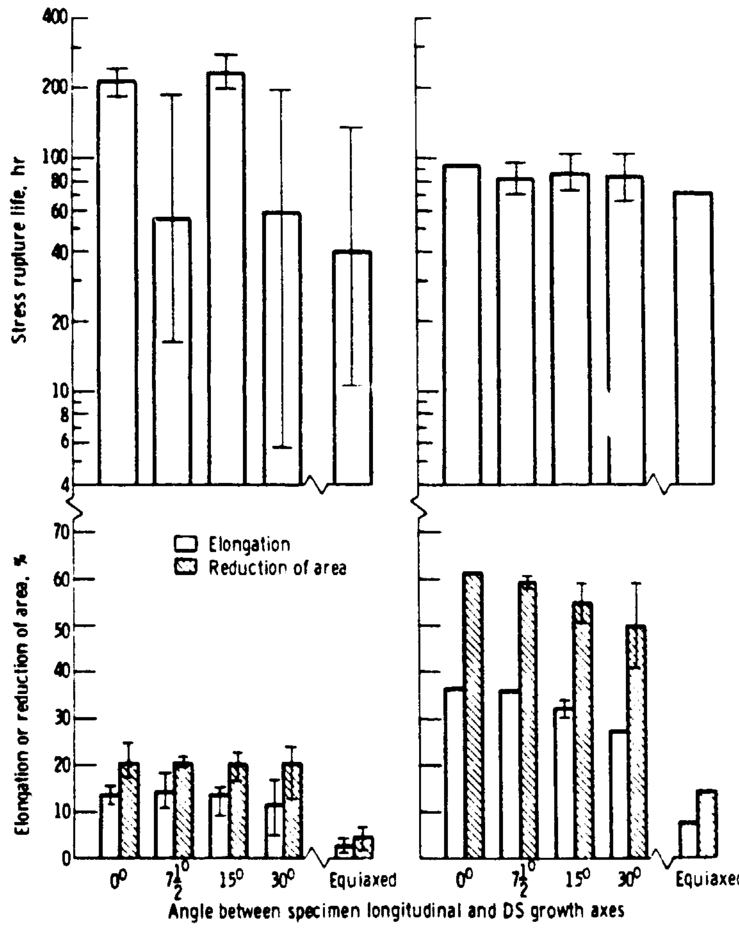
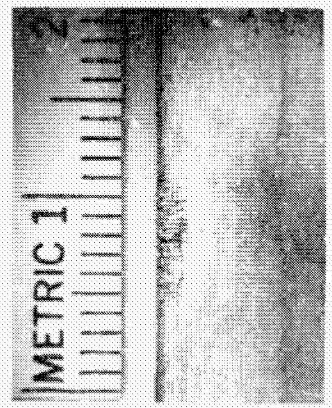
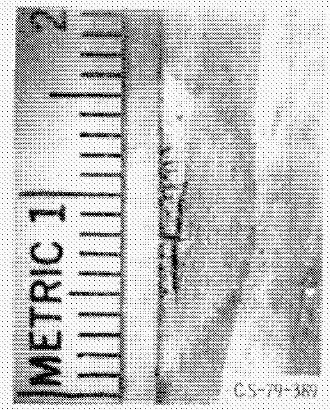


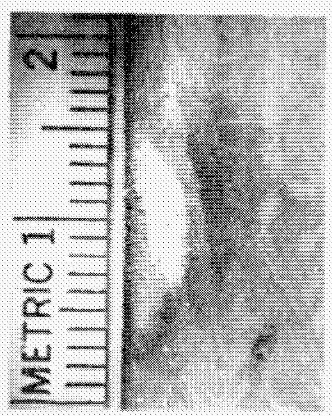
Figure 7. - Variation of stress rupture properties for directionally solidified (DS) and conventionally cast Mar-M 247 as a function of DS grain orientation angle.



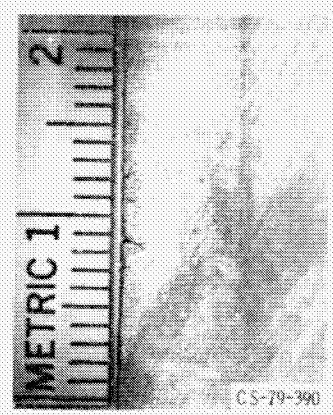
(a) 0^0 angle specimen after 500 test cycles, X5.



(b) $7\text{-}1/2^0$ angle specimen after 500 test cycles, X5.



) 15^0 angle specimen after 300 test cycles, X5.

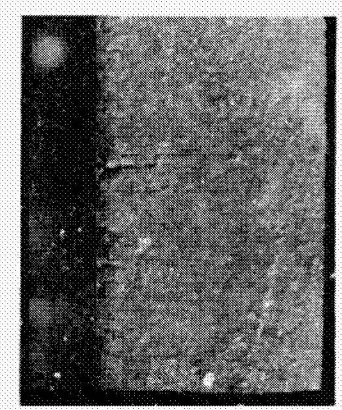


(d) 30^0 angle specimen after 300 test cycles, X5.

Figure 8. - Tested directionally solidified (D S) thermal fatigue wedges which have various angles between the specimen longitudinal and D S growth axes.

(a) Random polycrystalline specimen (as tested), X13.

(b) Random polycrystalline specimen (as etched), X5.



(c) D S specimen with $7\text{-}1/2^0$ angle between the specimen longitudinal and D S growth axes (as tested), X14.

(d) D S specimen with $7\text{-}1/2^0$ angle between the specimen longitudinal and D S growth axes (as etched), X14.

Figure 9. - Selected thermal fatigue wedges after 300 cycles of testing.

ORIGINAL PAGE IS OF POOR QUALITY